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INSTRUMENTATION FOR LIQUID HYDROGEN DENSITY MEASUREMENTS USING AN OPEN-ENDED MICROWAVE CAVITY

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16. Abstract

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SUMMARY

Two instrument systems that are used to make automatic and continuous measurements of resonant frequency are described and compared. These instruments can be used in conjunction with an open-ended microwave cavity to continuously monitor the density of liquid hydrogen in a flow system. Also described is a prototype model of a cryogenic flow line section with a build-in cavity. A review of hydrogen density measurements using an open-ended microwave cavity is also presented.

INTRODUCTION

To determine the total mass of a quantity of liquid hydrogen, the density of the hydrogen must be measured in addition to its volume since liquid hydrogen is a very compressible fluid. It was recently demonstrated that an open-ended microwave cavity can be used to make accurate hydrogen density measurements (refs. 1 to 3).

This method of density measurement in conjunction with a volumetric flowmeter is particularly useful for measuring mass flow rate or total mass transfer in a flow line. The body of the cavity can form a segment of the flow line, and the open ends allow the hydrogen to flow freely through the cavity without appreciable pressure drop.

In a liquid-hydrogen transfer system, it is difficult to produce a flow free of bubbles. The microwave cavity has the ability to accurately measure the average density of two-phase hydrogen (solid-liquid (slush) or liquid-gas) under limited conditions. It has been demonstrated experimentally (ref. 3) that density measurements using the cavity are not deteriorated appreciably by the presence of small and evenly distributed bubbles in the liquid.

The density measurement is predicted on the measurement of the resonant frequency of the cavity. In order to make mass flow rate or total mass transfer measurements, the resonant frequency must be measured continuously and processed to obtain density. The density measurement may then be combined with a volumetric flow rate measurement and further processed to obtain mass flow rate or total mass transfer. The processing of these measurements can be done quite simply by using commercially available, low cost computer modules.

Two instruments were developed to facilitate the continuous measurement of resonant frequency: a resonant frequency tracking system (REFTS) and a cavity tuned oscillator (CTO). A typical flow line section with a built-in cavity was also constructed and tested. This report will be primarily concerned with a detailed discussion of the theory of operation and performance of the flow line section and the two instruments, REFTS and CTO. To facilitate the discussion of these instruments, a cursory review of the theory of the open-ended cavity and liquid-hydrogen density measurements using this cavity is presented.

REVIEW OF DENSITY MEASUREMENTS USING AN OPEN-ENDED MICROWAVE CAVITY

Theory of Open-Ended Cavity

A theoretical analysis of the open-ended microwave cavity is covered in detail in reference 1. A diagram of the cavity is shown in figure 1. It consists of a circular wave-guide of radius b, which is terminated at each end with thin coaxial cylindrical partitions

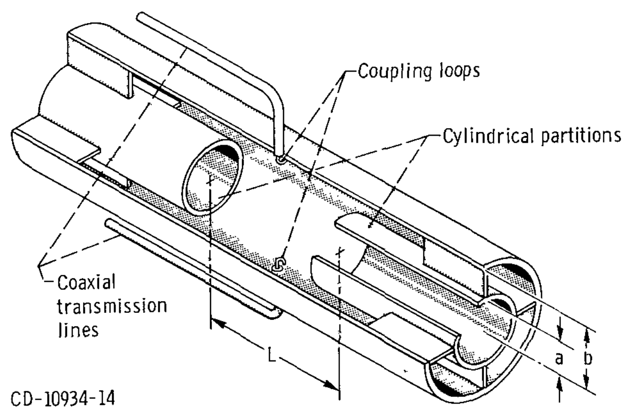


Figure 1. - Model of open-ended cavity.

of radius a that are separated by a distance L. Microwave energy is supplied to the cavity by small loops at the ends of coaxial transmission lines protruding through the side wall. If the cylindrical partitions are sufficiently long (ref. 1), they will act as perfect reflectors to the microwave energy over a frequency range that is dependent on the dimensions a and b. The cavity is resonant when the spacing of the partitions is adjusted so that the reflections are constructive. This condition occurs when the spacing L is approximately an integral multiple of one-half wavelength.

The required spacing for the TE_{011} mode of oscillation is shown in figure 2 in the form of curves of L/b against the dimensionless resonant frequency k_0b for typical values of the parameter b/a. The free-space wave number k_0 is equal to $2\pi f_0/c$, where f_0 is the resonant frequency of the cavity when it is evacuated and c is the velocity of light. The curves of figure 2 were computed by assuming that the cavity walls are perfectly conducting and that the partitions are infinitely thin. The TE_{011} mode of oscillation was selected because of its high Q.

The resonant frequencies predicted by the curves in figure 2 are for the case when

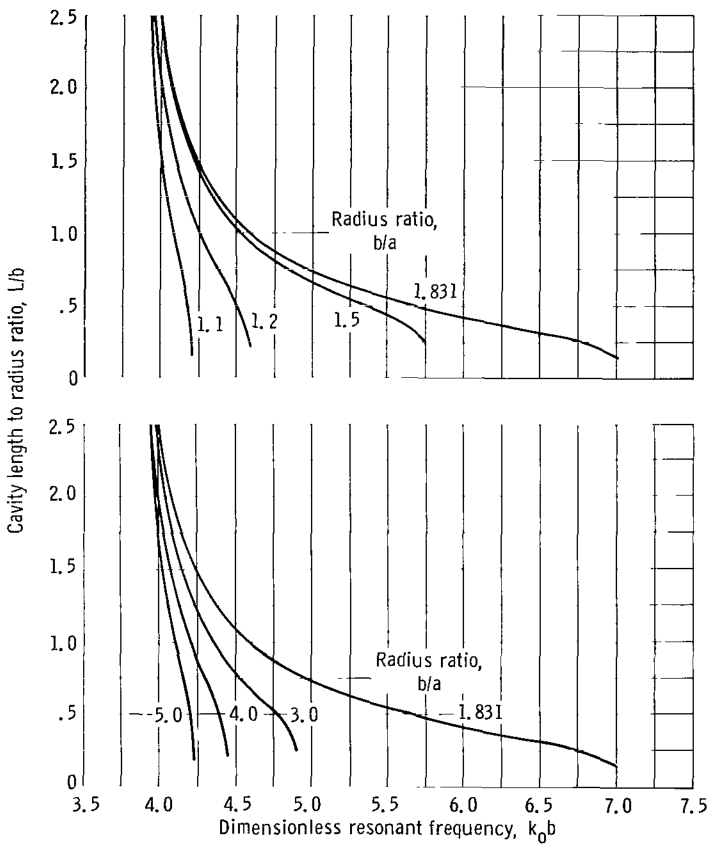


Figure 2. - Design curves for determining TE_{011} mode resonant frequency for constant values of radius ratio.

the cavity is evacuated. It can easily be shown that if the cavity is completely filled with a homogeneous, isotropic, dielectric material of relative dielectric constant K, the resonant frequency will be reduced by a factor $1/\sqrt{K}$. Thus, if f is the resonant frequency when the cavity is filled with a dielectric and, if f_o is resonant frequency when it is evacuated, then

$$K = \left(\frac{f_o}{f}\right)^2 \tag{1}$$

(Symbols are also defined in the appendix.) Equation (1) is the basic equation that is used to relate the relative dielectric constant of hydrogen to measured resonant frequencies.

Dielectric Constant and Density Relation

In practice, the Clausius-Mossotti equation is normally used to relate the density of hydrogen to its relative dielectric constant. The standard form of this equation is

$$\rho = \frac{3\epsilon_o m}{\alpha}\left(\frac{K - 1}{K + 2}\right) \tag{2}$$

where ρ is the mass density of hydrogen, K the relative dielectric constant, m the mass of a hydrogen molecule, α the average polarizability of a hydrogen molecule, and ϵ_o the electric permittivity of free space.

The Clausius-Mossotti equation is a derived equation that is based on the assumption that each molecule sees an internal field given by the Lorentz local field formula (ref. 4, p. 177). Böttcher has shown that the Lorentz formula gives the average internal field over the whole dielectric rather than the internal field that each molecule experiences (ref. 4, pp. 177 to 181). Thus, the Clausius-Mossotti equation is in error. This error may become large, particularly at high densities.

A more accurate formula for computing the density from relative dielectric constants has been derived by Böttcher (ref. 4, pp. 205-212). Böttcher's formula is based on a model for computing the internal field that pictures the molecule under study to consist of a polarizable point dipole centered in a spherical void. The radius of the void a_o corresponds to the molecular radius. The remaining molecules are assumed to act like a homogeneous dielectric medium. The result of this derivation is formulated in Böttcher's equation:

$$\rho = \frac{m\epsilon_o}{3\alpha} \frac{(K - 1)(2K + 1)}{K} - \frac{m}{6\pi a_o^3} \frac{(K - 1)^2}{K} \qquad (3)$$

A slight rearrangement of this equation reveals that a plot of $3K\rho/[(K - 1)(2K + 1)]$ against $(K - 1)/(2K + 1)$ is a straight line of slope $-m/2\pi a_o^3$ and intercept $m\epsilon_o/\alpha$. Such a plot, which also shows a representative sample of Stewart's data (ref. 5), is presented in figure 3. Stewart's experimental data consist of 205 points of dielectric constant as a function of density for parahydrogen for the density range from 2 to 80 kilograms per cubic meter. The error in these data is estimated to be less than 0.1 percent in density. The straight line shown in figure 3 is a least-percentage-error-squared fit to Stewart's data. The line has a slope of -55.31 kilograms per cubic meter and an intercept of 332.2 kilograms per cubic meter. It was concluded from an analysis of these data (ref. 3) that Böttcher's equation relates the density of parahydrogen to its

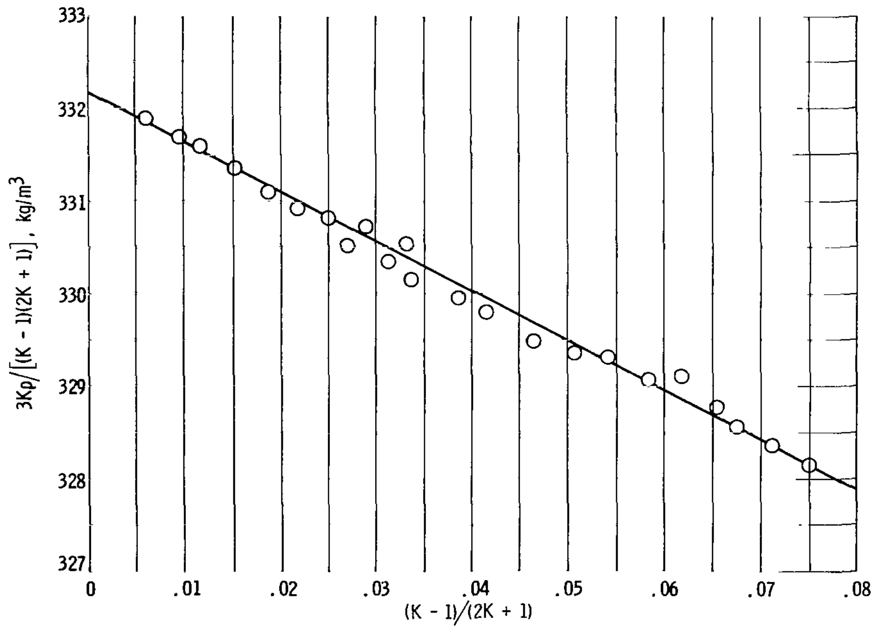


Figure 3. - Least-percentage-error-squared fit to Stewart's data (ref. 5).

dielectric constant with an error less than 0.1 percent over the range of densities from 2 to 80 kilograms per cubic meter.

Dielectric Constant of Two Phase Hydrogen

The basic equations that relate the cavity resonant frequency to the density of hydrogen may no longer be accurate if the hydrogen is nonhomogeneous, as is the case if bubbles are present. If a cavity is filled with a two-phase mixture, it will still resonate, but equation (1) will yield an effective dielectric constant K_{eff} of the mixture. If this value of K_{eff} is substituted into equation (3), an effective density of the mixture can be computed. The effective density is, of course, not the actual density. The difference between the two densities depends on the amounts and locations of each phase in the cavity and can be computed only if the amounts and locations are completely specified.

Taylor (ref. 6) has shown that the effective relative dielectric constant of a mixture that consists of liquid with relative dielectric constant K_l and bubbles with relative dielectric constant K_g is given by

$$K_{eff} = K_l - \frac{\delta K_{eff}(K_l - K_g)}{(1 - N)K_{eff} + NK_g} \tag{4}$$

where δ is the fraction of the total volume that is occupied by the gas and N is the depolarization factor for the bubbles. The depolarization factor is a function of the bubble shape and orientation with respect to the electric field, but it is independent of the absolute size of the bubble. Equation (4) is a derived equation that is based on the assumption that the fraction of the total volume occupied by the gas is very small (i.e., $\delta^2 << 1$) and that the bubbles are uniformly distributed in the liquid and have a mean radius r_e that is much less than the wavelength λ at which K_{eff} is measured. Typically, r_e should be of the order $0.01\ \lambda$ or less (ref. 3).

Figure 4 shows the percentage difference between the effective and the actual density as a function of δ. The bubbles are assumed to be either spherical or oblate spheroidal, which are the common shapes found in practice. The values shown are for saturated liquid and gaseous hydrogen at atmospheric pressure. For spherical bubbles, the difference may be neglected (0.01 percent for $\delta = 0.1$). As the eccentricity of the bubbles increases, the difference between the actual and effective density increases, going positive or negative depending on the orientation of the bubbles with respect to the electric field in the cavity. If the bubbles are randomly oriented, which occurs when turbulence is present, these differences will tend to cancel, giving a much smaller net difference than the

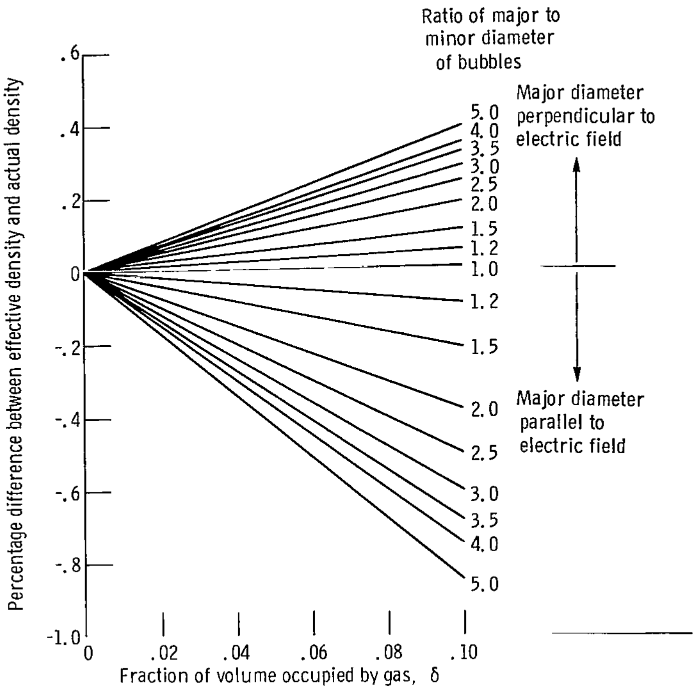


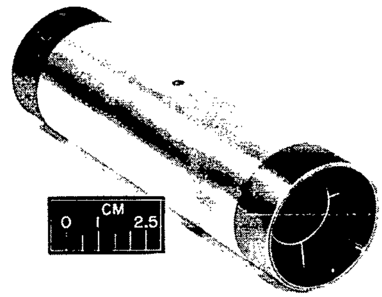
Figure 4. - Theoretical percentage difference between effective density and actual density against fraction of volume occupied by gas for oblate spheroidal hydrogen gas bubbles uniformly distributed in liquid hydrogen. Relative dielectric constant of liquid, 1.2297; relative dielectric constant of gas, 1.0040; liquid density, 70.784 kilograms per cubic meter; gas density, 1.3378 kilograms per cubic meter.

extremes shown. Thus, equation (3) can also be used to relate dielectric constant to density for a two-phase mixture of liquid with small, uniformly distributed gas bubbles.

The difference between the effective and actual density can also be computed for other configurations of liquid and gas in the cavity. The main difficulty, however, is not in calculating these differences, but in having the liquid and gas assume a known configuration so that these calculations will apply. The configuration analyzed, liquid hydrogen with small uniformly distributed gas bubbles, appears to be a reasonable configuration to enforce. In a flow line, for example, a screen or mixing device can be placed upstream from the cavity to break up the large bubbles and to generate turbulence to uniformly distribute and randomly orient the bubbles.

FLOW LINE SECTION

Figure 5 shows the prototype model of a flow line section with a built-in cavity. Three views are shown at different stages of construction.



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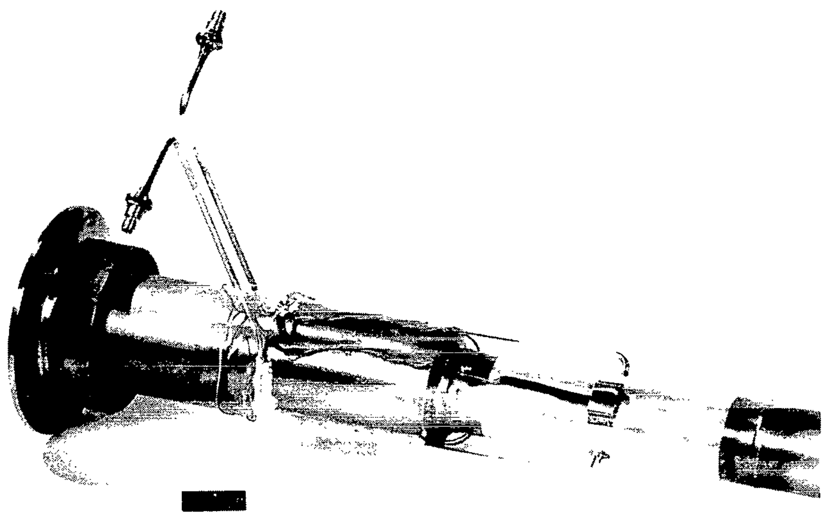
(a) Cavity subassembly.



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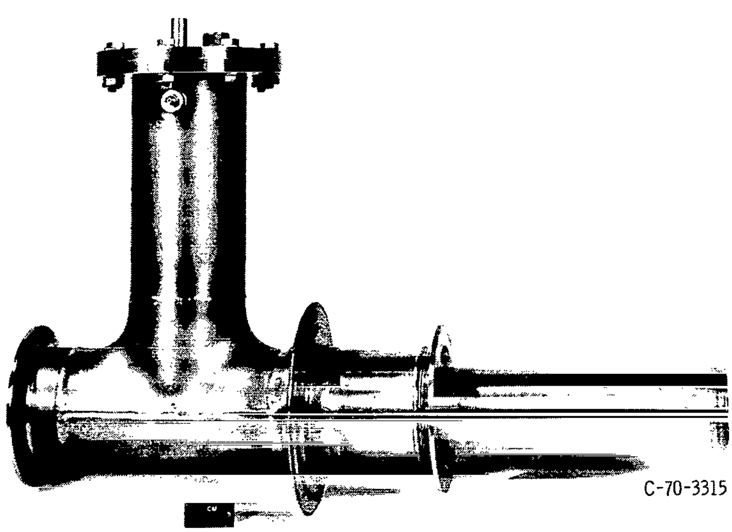
(b) View showing location of cavity and routing of transmission lines.



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(c) Completed flow line section.

Figure 5. - Prototype model of flow line section with built-in cavity.

Figure 5(a) illustrates the construction of the cavity subassembly. The body of the subassembly was made using a stainless-steel tube with an inside diameter of 39 millimeters (1.53 in.) and a wall thickness of 1.5 millimeters (1/16 in.). This is the same tube size and material that is used to construct standard commercial flow line sections of this nominal size. The flow line tube size is the starting point in the design of the cavity. It determines the dimension b. Then, the curves in figure 2 are used to relate a, L, and f_o. Two of these variables may be selected by the user to suit his experimental conditions or available microwave equipment. It is wise, however, to make L/b one or larger to minimize changes in resonant frequency due to temperature gradients in the cavity. It can be seen that dimension a can change more rapidly during temperature transients than either L or b, since the cylindrical partitions are much less bulky.

The partitions and their supporting ribs are made of the same type of stainless-steel alloy as used for the cavity body. If the coefficients of thermal expansion are the same for all parts of the subassembly, the parameters L/b and b/a will be constant for all temperatures at equilibrium conditions.

To minimize the obstruction to flow, the thicknesses of the cylindrical partitions and their supporting ribs were made as small as possible without sacrificing structural integrity. The ratio of the area of obstruction to the flow area in the prototype model is approximately 3.0 percent.

The cavity subassembly was plated with silver (1.25×10^{-2} mm minimum thickness or 20 "skin depths" at 10 GHz) to increase the value of Q_o which is the quality factor of the cavity. The quality factor is defined as 2π times the ratio of the energy stored in the cavity to the energy dissipated in the cavity walls per cycle of oscillation. If the cavity walls are perfectly smooth, it can be shown that Q_o is inversely proportional to the square root of the resistivity of the walls of the cavity. At room temperature the ratio of the resistivities of silver and stainless steel is 1/50, which results in an improvement in Q_o by a factor of about 7 from an unplated cavity. However, the more significant asset of silver is that its resistivity decreases much more rapidly with decreasing temperature than does that of stainless steel. At liquid-hydrogen temperatures (20 K) the ratio is 1/2500, giving a fiftyfold increase in Q_o. This entire increase can not be realized, however, because the surface roughness limits the maximum value of Q_o. For the prototype cavity, Q_o was 23 000 at room temperature and 65 000 at 20 kelvin.

The value of Q_o is the unloaded Q of the cavity; that is, the value neglecting the effects of the transmission lines and coupling loops. If these effects are accounted for, it can be shown (ref. 7) that the loaded Q for a transmission cavity is

$$Q_L = \frac{Q_o}{1 + \beta_1 + \beta_2} \tag{5}$$

where β_1 and β_2 are the coupling coefficients of the transmission line coupling loops. The transmission factor T of the cavity, which is the fraction of the available power transmitted through the cavity, is equal to

$$T = \frac{4\beta_1\beta_2}{(1 + \beta_1 + \beta_2)^2} \tag{6}$$

It can be seen that increasing the coupling coefficients will increase the transmission factor, but it will lower Q_L. A value of Q_L equal to 8000 was selected, which is the lowest value that will insure liquid-hydrogen density measurements to an accuracy of about 0.1 percent. If the Q_L were lower, the dominant error in the density measurement would be due to the uncertainty in the cavity resonant frequency. If the Q_L were higher, the error due to the uncertainty in resonant frequency would be reduced, but the error in density is still limited by the uncertainty in the dielectric constant-density relation which is about 0.1 percent. The automatic measurement of the cavity resonant frequency also becomes more difficult and costly when Q_L is increased.

The size of the coupling loops was adjusted to obtain the proper value for Q_L. In order to arrive at the desired value of 8000 for Q_L at 20 kelvin, the required values for β_1 and β_2 were computed using equation (5) and then converted to their room-temperature values. These values were used to compute Q_L at room temperature. It was for the latter value of Q_L that the loops were adjusted.

Figure 5(b) shows the flow line section in its late stages of assembly. Only the vacuum jacket is needed for the completed assembly which is shown in figure 5(c). Figure 5(b) shows the location of the microwave cavity and the routing of the transmission lines.

The transmission lines constitute a heat path from the connectors on the outside which are at ambient temperature to the flow line which is at liquid-hydrogen temperature. Since it is not generally desirable to add large amounts of heat to a hydrogen flow line, the transmission lines used were long (0.35 m) and thin (3.58 mm diam) to minimize the heat flow. In addition, the transmission lines were formed so that nearly one third of the length between the terminals and the cavity made thermal contact with the surface of the flow line. This prevented all the heat from being added to the flow line at one point. An epoxy which is loaded with silver was used to bond the line to the surface to insure good thermal contact.

The transmission line, which is a semirigid coaxial cable, consists of a 3.58-millimeter (0.141-in.) diameter copper tube for its outer conductor, a 0.9-millimeter-diameter (19 gage) solid copper wire for its center conductor, and a solid Teflon dielectric. The connectors are commercially available, hermetically sealed, feed-through coaxial connectors.

A good seal is required to keep hydrogen from leaking at the ports where the transmission lines enter the cavity. To do this reliably, the outer conductors of the coaxial lines were soldered to the wall of the cavity, and the connectors sealed the lines at the warm ends. Since the solid Teflon dielectric does not form a vacuum seal between the center conductor and the outer conductor of the transmission lines, a long thin layer of hydrogen gas is trapped in the cables behind a room-temperature seal. This same principle is also used in joining flow line sections.

Originally, the complete seal was made at the cavity wall by using a Kovar and glass feed through. Not only was this seal unreliable because of the thermal stress it experienced, but it also presented an excessive electrical load on the transmission line which lowered the Q.

The prototype version of the flow line section has two platinum resistance temperature sensors bonded to the outside of the cavity body. These were installed to make thermal cycling tests on the prototype model and will not be needed on subsequent models. Figure 5(b) shows the radiation shield, which covers the sensor, and the electric lead wires.

In order to use the flow line sensor, it is necessary to determine f_o, the resonant frequency when the cavity is evacuated, at the operating temperature. It is not adequate to use the value for f_o at room temperature, since the change in resonant frequency from room temperature to liquid-hydrogen temperatures is significant (40 MHz in the prototype model). This measurement is most easily accomplished by filling the cavity with liquid hydrogen of known temperature and pressure and, hence, known density and then measuring its resonant frequency. Equations (1) and (3) can then be used to solve for f_o. It is generally not necessary to determine f_o at more than one temperature if only liquid hydrogen is used, since a temperature change of 10 kelvin in the vicinity of 20 kelvin produces a density error of only 0.01 percent because of changes in f_o with temperature. The change in f_o with pressure is also negligible. In the prototype model a pressure variation of one atmosphere causes about 0.01 percent error in measured density.

One problem that was considered, however, is zero shift due to thermal cycling. Zero shift is one of the major problems in the capacitance sensors used for measuring hydrogen density. The capacitor plates or grids often distort or shift when subjected to thermal cycling due to the differences in coefficients of expansion between the metallic capacitor plates or grids and the insulating supporting structure. Such shifts were not expected from the open-ended cavity because it is constructed entirely from one material.

The flow line section was tested, however, to insure that there were no permanent deformations in the cavity due to thermal cycling. The test was performed by measuring the resonant frequency f_o with the cavity evacuated at liquid-nitrogen temperature after each of several transitions from room temperature to liquid-nitrogen temperature. Liquid nitrogen was used instead of liquid hydrogen because evacuating a cavity immersed in hydrogen is too hazardous. Using liquid nitrogen is a reasonable substitute because stainless-steel experiences approximately 95 percent of the thermal contraction, when it is cooled from room temperature to liquid-nitrogen temperature (77 K), that it would experience being cooled to liquid-hydrogen temperature (20 K). The test was performed by sealing both ends of the line section, filling the vacuum jacket and the flow line with gaseous nitrogen, and then immersing the line section into a liquid-nitrogen bath. The nitrogen gas provided a thermal path to the flow line. When the temperature sensors indicated that the cavity walls were at 77 kelvin, the nitrogen gas was pumped out. The pumping process supercooled the flow line slightly since some of the nitrogen gas had condensed to liquid. Then resonant frequency readings were taken as the cavity walls warmed. This procedure was repeated four times. Figure 6 shows a plot of the resonant

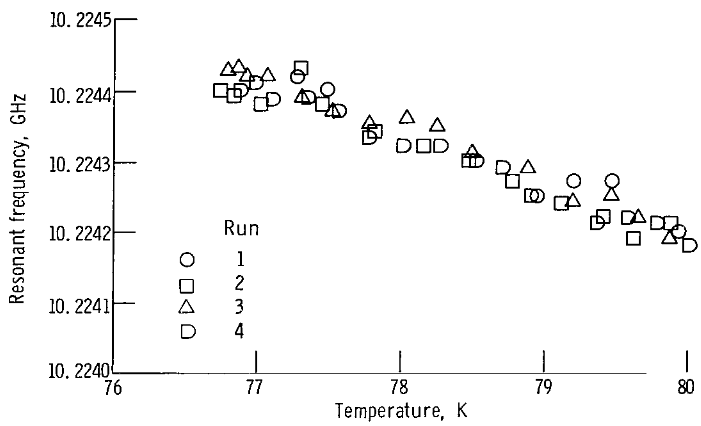


Figure 6. - Effect of thermal cycling on resonant frequency.

frequency data as a function of temperature. Note that the scatter of the data is less than 100 kilohertz, which is less than 10 percent of the cavity bandwidth. The slope is the drift rate of f_0 with temperature near 77 kelvin. The thermal coefficient of expansion for stainless steel is lower at 20 kelvin by an order of magnitude; thus, the drift rate at the operating temperature would also be lower by an order of magnitude. Apparently there is no noticeable deformation due to repeated thermal cycling.

AUTOMATIC RESONANT FREQUENCY MEASUREMENT

In order to take full advantage of the flow line sensor, it is necessary to have an instrument that will automatically measure and record the resonant frequency of a cavity. Digital frequency counters are commercially available that can automatically measure the frequency of a microwave generator. The measured frequency can be displayed on a digital readout or it may be recorded on a printer, punched tape, computer cards, or magnetic tape. It is only necessary, therefore, to have an instrument that will generate a microwave signal equal to the resonant frequency of a cavity. Two different instruments were developed for generating this signal: a resonant frequency tracking system and a cavity tuned oscillator. A description of both instruments will be presented and their relative merits will be discussed in the following sections.

Resonant Frequency Tracking System (REFTS)

The block diagram in figure 7 illustrates the operation of the REFTS. A phase detector is used to develop an error signal by sensing the phase of a frequency modulated signal, which shifts 180° as the microwave frequency passes through the resonant frequency of the cavity. The error signal is used to generate a control voltage which tunes the microwave voltage controlled oscillator (VCO) to the cavity's resonant frequency.

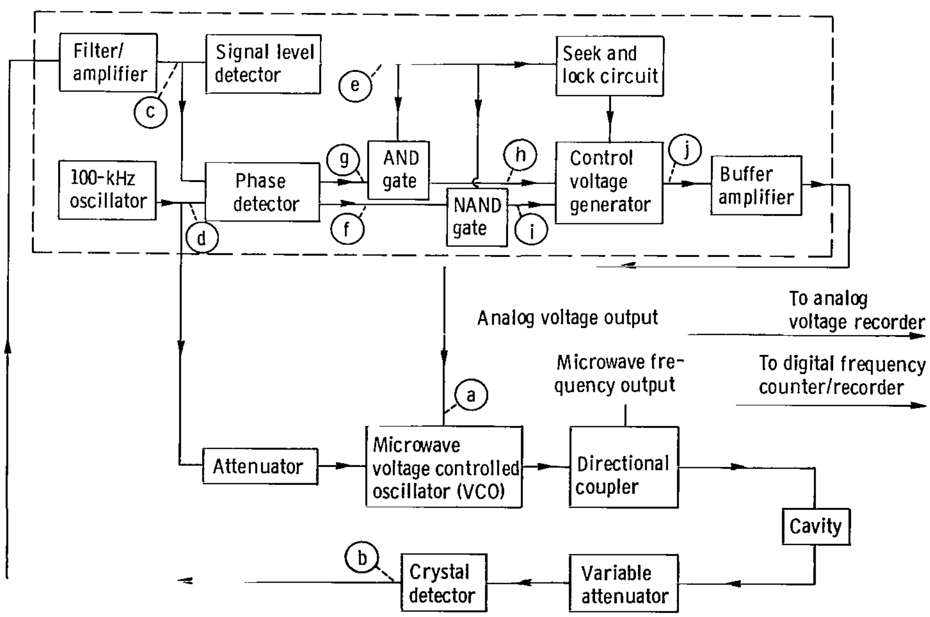
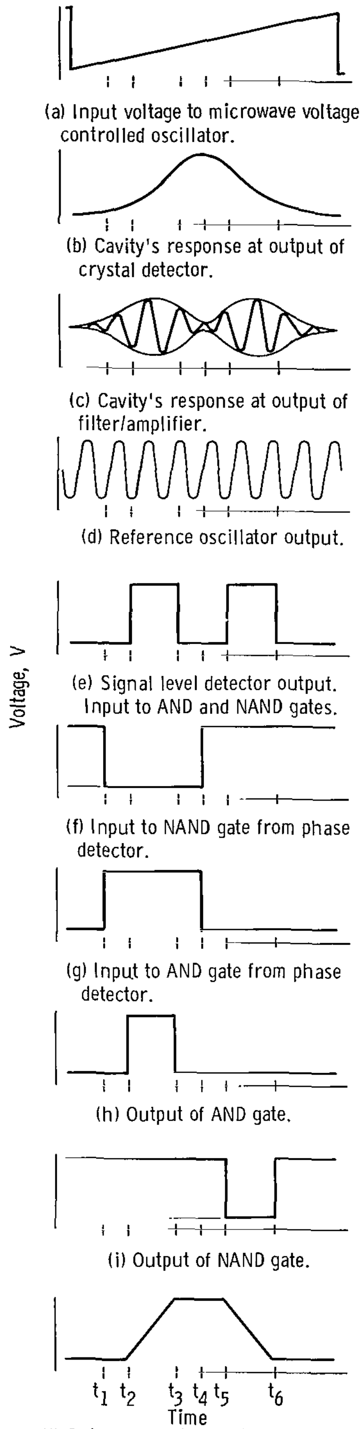


Figure 7. - Block diagram of resonant frequency tracking system (REFTS). (The letters in circles refer to the waveforms shown in fig. 8.)

The operation of this instrument can be explained best by describing the system in open-loop operation. If the output of the buffer amplifier is disconnected from the microwave VCO and a voltage ramp generator is connected in its place, the voltage waveforms illustrated in figure 8 will be generated. The test points for these waveforms are identified in figure 7 with their corresponding letter. The voltages for the waveforms are not to scale, but the time scales are all identical. For purposes of illustration, the magnitude of the voltage ramp (fig. 8(a)) is made just large enough to deviate the frequency of the VCO over the range of the cavity's response, and the period of the ramp signal is set equal to 90 microseconds, which is equal to nine cycles of the 100-kilohertz reference oscillator (fig. 8(d)). This allows all circuit operations within the REFTS to be illustrated on one time scale. Moreover, since the frequency of the VCO deviates over a fixed frequency range during this same time period, the waveforms are also a function of frequency. This is particularly evident in figure 8(b), which is the frequency response of the cavity. In the prototype model a positive going voltage increases the frequency of VCO. Therefore, the frequency increases with time (from left to right) in figure 8.

When the microwave VCO is frequency modulated by a signal from the reference oscillator, there is superimposed on the response curve of figure 8(b) at the output of the crystal detector a very low-amplitude, 100-kilohertz sinewave voltage. The filter-amplifier circuit filters out the low-frequency components (the response curve) and amplifies the 100-kilohertz signal. The amplitude of this signal (fig. 8(c)) is proportional to the slope of the response curve, and the phase shifts 180° as the microwave frequency passes through the center frequency of the cavity. The phase detector compares the phase of this signal with the reference signal (fig. 8(d)) from the 100-kilohertz oscillator and produces the waveforms in figures 8(f) and (g). That is, one output of the phase detector (fig. 8(f)) is zero when the signals are in phase (from t_1 to t_4), and it is positive when the signals are out of phase or if the amplifier output is zero. A voltage inverter, also in the phase detector, produces the complement as shown in figure 8(g). The signal level detector converts the amplitude information (fig. 8(c)) into the waveform shown in figure 8(e). The output of the signal level detector is zero unless its input signal is greater than a preset threshold value. The signal at t_2, t_3, t_5, and t_6 is equal to this threshold value. The detected phase and amplitude information are fed into an AND gate and a NAND gate. Each gate produces a unique signal. The AND gate produces a signal (fig. 8(h)) that is positive only when the outputs of the signal level detector (fig. 8(e)) and the phase detector (fig. 8(g)) are both positive (from t_2 to t_3). This occurs when the microwave VCO frequency is lower than the center frequency of the cavity. The NAND gate produces a signal (fig. 8(i)) that goes to zero only when the output of the signal level detector (fig. 8(e)) and the complementary output of the phase detector (fig. 8(f)) are both positive (from t_5 to t_6). This occurs when the VCO frequency is higher than the cavity center frequency. These signals trigger the control voltage generator, which increases



(a) Input voltage to microwave voltage controlled oscillator.

(b) Cavity's response at output of crystal detector.

(c) Cavity's response at output of filter/amplifier.

(d) Reference oscillator output.

(e) Signal level detector output. Input to AND and NAND gates.

(f) Input to NAND gate from phase detector.

(g) Input to AND gate from phase detector.

(h) Output of AND gate.

(i) Output of NAND gate.

(j) Output of control voltage generator and buffer amplifier.

Figure 8. - Voltage waveforms of the REFTS (resonant frequency tracking system) in open-loop operation.

the voltage output when it is triggered by the AND gate signal and decreases the voltage when triggered by the NAND gate signal as shown in figure 8(j)). The buffer amplifier has a gain of one. It is used for impedance transformation between the control voltage generator, which has a high output impedance, and the microwave VCO, which has a low input impedance.

Note that the description of the system operation is for the open-loop mode; the control voltage is not tuning the microwave VCO. It can be seen, however, that, when the loop is closed, the VCO frequency will increase if it is low and decrease if it is high. Thus, in normal closed-loop operation, the VCO frequency tracks back and forth about the cavity's center frequency with the average value of the VCO frequency equal to the cavity's center frequency. It should also be evident that there are no control signals when the VCO frequency is above or below the influence of the cavity's response or when it is equal to the center frequency of the cavity. The second condition is not really a problem because the VCO frequency is the correct output frequency. However, the possibility of the VCO frequency being beyond the influence of the cavity's response necessitates the inclusion of a seek-and-lock circuit to initially start the operation or to restart it after control has been lost.

The seek-and-lock circuit senses the output of the signal level detector (fig. 8(e)) through a time delay. When the signal level is zero for more than 10 milliseconds, the REFTS goes through the seek-and-lock mode of operation; that is, the control voltage generator is triggered to drive the VCO through a suitable frequency range. In the prototype model a front panel switch selects a low, medium, or high range which spans 0.3, 1.2, or 2.4 gigahertz, respectively. When the VCO frequency passes into the influence of the cavity's response, the seek-and-lock mode is terminated by a signal from the phase detector. The time duration in the seek-and-lock mode may be from 10 to 500 milliseconds.

The circuits that are enclosed by the dashed lines in figure 7 were designed and constructed at Lewis. Figure 9 is a schematic diagram of these circuits. In order to use this system with transmission, reaction, and absorption cavities, a double-pole double-throw switch was incorporated in the circuit to reverse the two outputs from the phase detector to the two gates. This switch is needed only when more than one type of cavity is used. Changing from a reaction or absorption type of cavity to a transmission type inverts the response curve, which requires the phase detector outputs to be reversed in order to maintain control.

The control voltage generator circuit is a group of four simple constant-current sources that charge or discharge a capacitor when one of the sources is triggered on. Only one source is on at any one time. Two of the sources are driven by the error signals, and the other two are driven by the seek-and-lock circuit. If the voltage to fre-

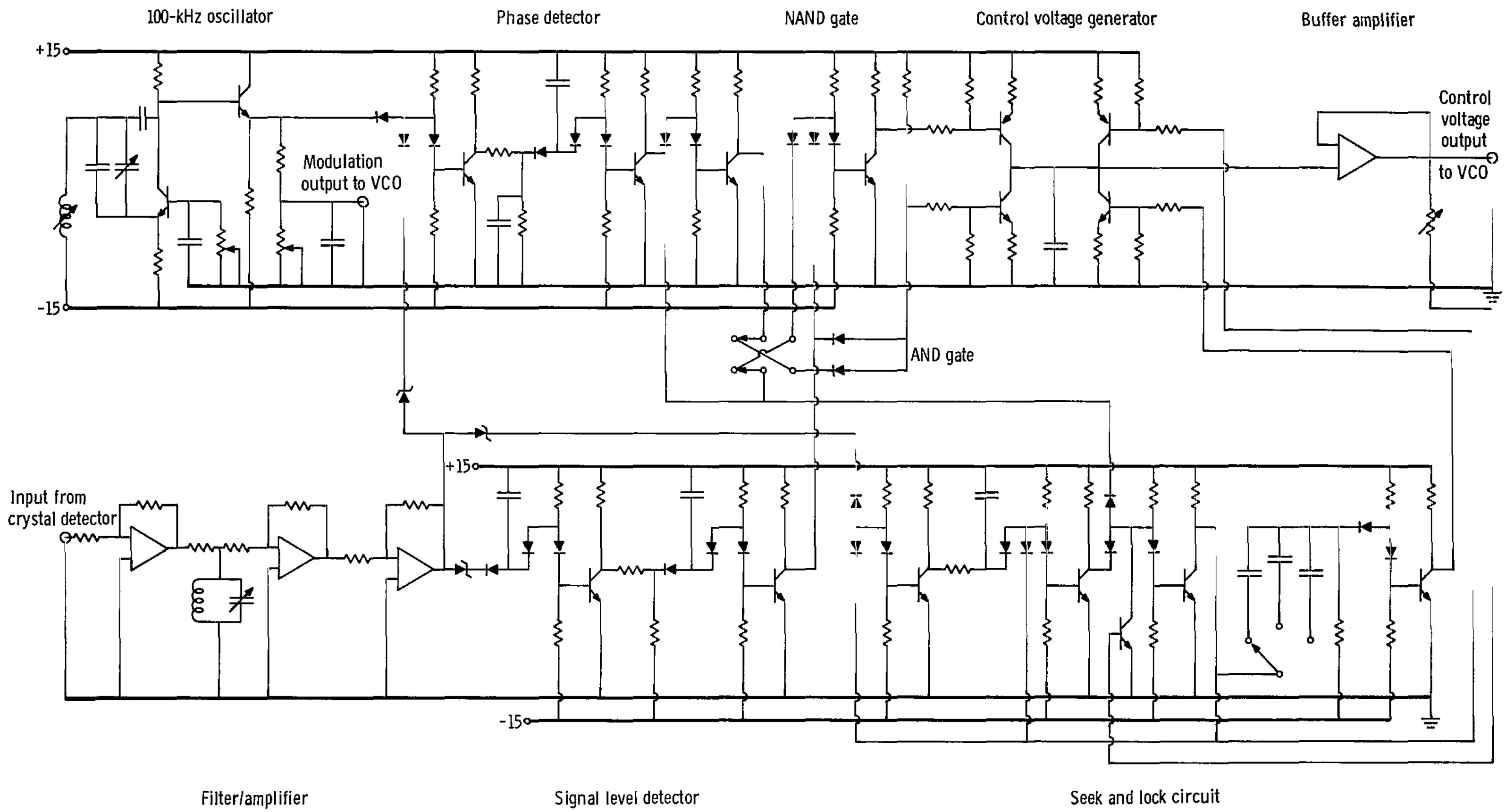


Figure 9. - Circuits constructed at Lewis.

quency transfer function of the microwave VCO is linear, the REFTS produces a constant slewing rate since a constant current into a fixed capacitor produces a linear voltage ramp. By adjusting resistance values in the current generator circuit, the user may set the slewing rate to suit his requirements. However, the slewing rate must not exceed the value that will drive the frequency beyond the influence of the cavity's response before a new error signal can be generated by the phase detector. In the REFTS the slewing rate was set at 9.6 gigahertz-per-second which is approximately the maximum allowable rate permitted by the phase detector.

A buffer amplifier with very high input impedance (greater than 5×10^6 ohms) was required to transfer the voltage information on the capacitor to the VCO. An FET operational amplifier with feedback circuitry that produced a voltage gain of one was used in the prototype model. The leakage from the capacitor was sufficiently low that the frequency change (due to leakage) during periods of no control was 100 megahertz per second. That is equivalent to a drift through the bandwidth of the cavity during the 10 millisecond delay in the seek-and-lock circuit.

The control voltage that is generated is dependent on the voltage-to-frequency transfer function of the VCO. If this function is known and if it is stable, the control voltage may be used to measure the frequency of the REFTS. Thus, the user has two options for frequency readout. When very accurate measurements (0.001 percent) at a slow rate (less than five samples per second) are required, the microwave output may be sampled and measured with a digital frequency counter. If high-speed (transient) data are required and some sacrifice in accuracy is acceptable, then the control voltage may be measured and converted to frequency.

Figure 10 shows the frequency response of the prototype model. The data indicate that the REFTS breaks lock when the resonant frequency changes faster than the slewing rate, as one might expect. The cavity used in the test was a commercial wavemeter having solid plates at the end walls with one end wall movable. The data were taken by mounting the cavity on a solid support and mounting its movable end wall on a dynamic shaker. Thus, the length of the cavity and, hence, its resonant frequency were changing at a sinusoidal rate. The displacement was increased gradually at each shaker frequency until the system failed at two types of failure modes. The displacement was recorded for each of the failure modes: One was when the REFTS broke lock, that is, when it went into the seek-and-lock mode; the other was when the instrument ceased to track the driving function - but only for short periods of time compared with the 10-millisecond delay required to activate the seek-and-lock circuits. The failures were detected by observing the control voltage using an oscilloscope. For small displacements of the cavity end wall, the voltage varied sinusoidally, as was expected, which indicated that the REFTS was locked to the cavity frequency. When the REFTS first began to fail, the control voltage waveforms appeared to be similar to a rectified sinewave, which indicates that the

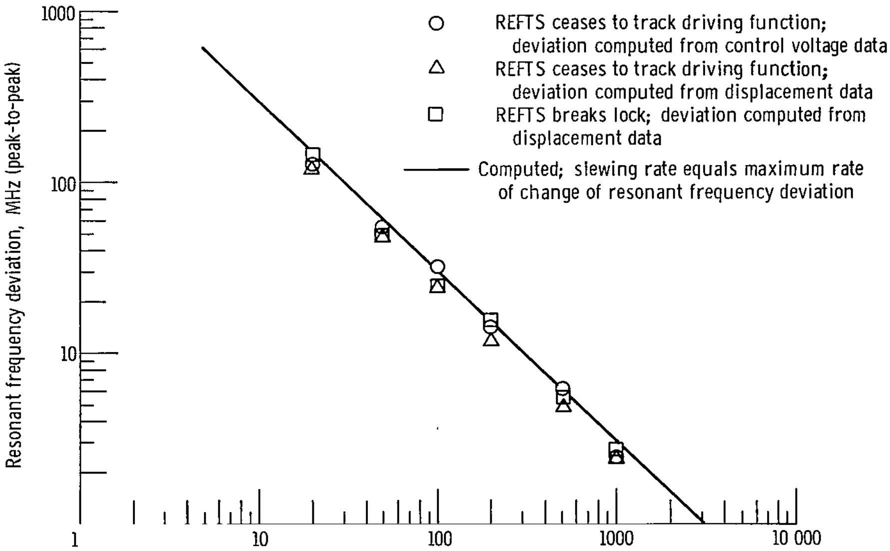


Figure 10. - Frequency response of REFTS.

REFTS continued to operate for short intervals at the last known frequency during the interruptions in control. As end wall displacement was further increased, the period where control was lost increased until it reached the 10-millisecond delay in the seek-and-lock circuit when the FEFTS broke lock.

The results show that, if the cavity center frequency deviates only a small amount, then it can do so at a very rapid rate, and the REFTS system will continue to track it. However, if the deviation is large, then the rate of change of frequency must be limited (less than 9.6 GHz/sec in the prototype model) or the system will fail to track the cavity frequency.

To interpret this frequency tracking capability in terms of changes in hydrogen density, visualize a flow line containing liquid hydrogen and small hydrogen gas bubbles which are introduced into the liquid in such a manner that the fraction of the volume occupied by gas is changing in a sinusoidal manner from zero to some peak value δ. As the frequency of the sinusoidal variation of gas volume increases, the peak value of δ must decrease if the REFTS is to remain locked. Table I shows the peak value of δ for typical frequencies for a cavity with f_o equal to 10 gigahertz. The values shown are for liquid and gaseous hydrogen at the saturation point at 1 atmosphere of pressure.

TABLE I. - REFTS RESPONSE TO DENSITY VARIATIONS

Deviation frequency, Hz	Microwave frequency deviation (peak to peak), MHz	Density deviation, percent	Maximum gas volume, δ, percent
3000	1	0.1	0.1
300	10	1.0	1.0
30	100	10	10

Cavity Tuned Oscillator (CTO)

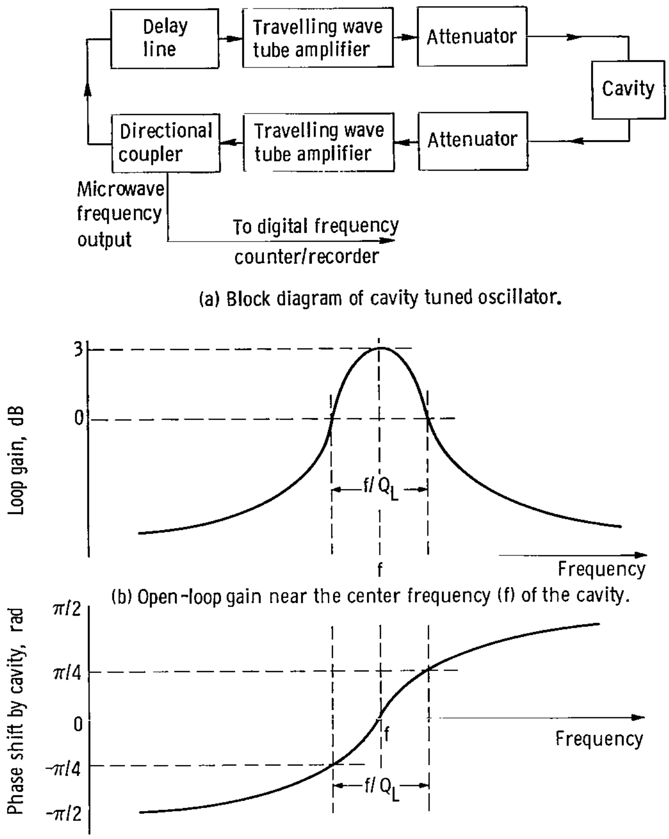
The block diagram in figure 11(a) illustrates the operation of the CTO. The oscillator consists of the loop formed by the delay line, traveling wave tube amplifiers, cavity, and attenuators. The directional coupler is not necessary for oscillation. It is inserted into the loop to provide a sample of the microwave signal for the frequency counter.

The necessary criteria for oscillation are that the loop gain be 0 decibel (dB) or greater and that the phase shift around the loop be an exact multiple of 2π radians. The loop gain as a function of frequency is dependent primarily on the transmission characteristics of the cavity as shown in figure 11(b). If the loop gain is adjusted to 3 dB at the center frequency of the cavity, then the system will oscillate if the phase criterion is met somewhere in the frequency range $f \pm (f/2Q_L)$, where $f/2Q_L$ is the difference in frequency between the cavity's center frequency and the 3 dB down points. Figure 11(c) shows that the cavity provides a $\pi/2$ radian phase shift between the 3-dB down points. Thus, to insure oscillation, a delay line is needed in the loop that will provide a phase shift of at least $3\pi/2$ radians whenever the frequency changes by as much as f/Q_L over the entire frequency range of interest. A delay line provides a phase change with angular frequency $(d\varphi/d\omega)$ equal to its delay time τ. Thus,

$$\tau = \frac{\Delta\varphi}{\Delta\omega} \geq \frac{\frac{3\pi}{2}}{2\pi \frac{f}{Q_L}} = \frac{3}{4} \frac{Q_L}{f}$$

If Q_L is equal to 8000 and the lowest resonant frequency is equal to 9.2 gigahertz, a time delay of at least 0.65 microsecond is required.

Obviously the CTO does not necessarily produce a signal that is precisely equal to the center frequency of the cavity. The frequency of oscillation can differ from the cav-



(a) Block diagram of cavity tuned oscillator.

(b) Open-loop gain near the center frequency (f) of the cavity.

(c) Phase shift by cavity near its center frequency (f).

Figure 11. - Diagrams illustrating the operation of the cavity tuned oscillator.

ity center frequency by as much as $f/2Q_L$. This represents a maximum error in resonant frequency measurement of 0.006 percent.

If the CTO were adjusted to operate exactly as described, in particular, if the gain were set equal to 3 dB at the cavity center frequency, there would be only one operating point; that is, there is only one frequency for which the loop gain is equal to or greater than 0 dB and the phase shift is some multiple of 2π radians. As the center frequency of the cavity increases (i.e., as the density decreases), this operating point will move across the cavity's response (right to left in fig. 11(b)) between the 3 dB points. Just when the operating point disappears on the left, a new one will appear on the right. This type of operation proved to be unstable over the desired frequency range, because amplifier gain is not normally constant as a function of frequency.

A better way to operate the CTO is to increase the loop gain slightly and/or increase the time delay. With higher gain or time delay, the new operating point appears before the other disappears. Tests have shown that when there are two or more possible operating points, the instrument will oscillate at the point that has the higher loop gain. Increasing the time delay also reduces the frequency error. In the prototype model a 1-

microsecond delay was used. The maximum frequency error was reduced to less than 0.004 percent, and the corresponding error in density due to the frequency error was less than 0.06 percent.

The time delay can be achieved using an electro-acoustic crystal device or a long waveguide or coaxial cable. The electro-acoustic crystal device is very small (about 30 cm^3) but tends to have high attenuation (about 60 dB for this application). The long waveguide has lower attenuation and cost but is very bulky. It was used in the prototype system, however, because size was not a factor. The crystal device may be preferable in other applications.

The time delay unit consisted of a WR-112 aluminum waveguide 258 meters long. The waveguide is coiled into a 0.35 cubic meter package. The measured attenuation for this line was 31.5 to 34.0 dB for the frequency range of 9.15 to 10.25 gigahertz. This was considerably higher than the attenuation that might have been expected (22.0 dB at 10.0 GHz) from published values (0.085 dB/m). The published values do not account for losses due to bends and coupling joints, however.

The remaining attenuation in the loop was about 16 dB because of the losses in the cavity the directional coupler, and transmission lines used for interconnecting the components. Therefore, at least 50-dB gain is needed by the amplifier.

Two traveling wave tube amplifiers were used with a combined gain of 65 dB. The additional gain permitted the insertion of attenuators at the input and output of the cavity to minimize frequency pulling by other components in the loop.

The ability of the loop to accurately track the cavity resonant frequency was verified by using a commercially available precalibrated tunable cavity. The frequency response of the CTO was not measured, but it is probably limited only by the time delay around the loop (1 μsec), that is, of the order of 1 megahertz.

Relative Merits of REFTS and CTO

The REFTS was originally designed and constructed with the expectation that it could meet almost all possible requirements. Tests have shown, however, that many of the commercial digital frequency counters that lock a harmonic of an internal oscillator to the input signal have difficulty in working properly in the presence of frequency modulation (FM) in the input signal. The REFTS in normal operation generates three types of FM signals. First, there is the 100-kilohertz modulation required to detect the error signal. The deviation of this signal is extremely small (30 to 100 kHz) and does not usually cause difficulty in the counters. The second type of FM is generated as the instrument tracks back and forth from one side of the cavity's response to the other. The deviation of this signal is less than f/Q (approximately 1.0 MHz). The deviation rate is of the order of

1000 hertz. It is dependent on the slewing rate of the REFTS and the bandwidth of the cavity. The third type of FM is the dynamics of the measured quantity; that is, the rate of change of the resonant frequency (or hydrogen density).

At the time of the release of this report, at least one commercial microwave digital counter is available that can produce accurate frequency measurements without interruption in the presence of all FM signals. During the previous year or two, great strides have been made in the state-of-the art of digital frequency measurement. It is anticipated that the FM problem in the REFTS will be insignificant in the near future.

When the resonant frequency changes rapidly and frequently, as it would if many large bubbles were present in a flow line, the REFTS may be triggered into the seek-and-lock mode too frequently. In extreme cases, it may spend most or all of the time searching for the cavity frequency. The CTO system will track the most severe cases. However, the measurement of data with a response that exceeds the maximum sampling rate of five samples per second in commercially available counters becomes sophisticated. Whereas, in the REFTS an analog voltage is inherently generated, the CTO system requires a discriminator to produce an analog voltage with the frequency information.

Resonant Frequency Data Processing

In the testing of the hydrogen density measurement system discussed in this report, relatively small quantities of data were taken (refs. 2 and 3). The resonant frequency data were recorded using a digital printer. Then, the data were transferred to computer cards and the Lewis central computer facility was used to obtain density.

Where a large volume of data is required, there are commercial units available that can be connected to the digital counter which will record the data directly on computer cards, punched tape, or magnetic tape, whichever is compatible with an available computer. Likewise the analog output may be recorded on magnetic tape or fed directly into an analog computer.

There are commercially available low-cost process computer circuits that can also be made part of the measurement system. In such a system the resonant frequency data can be processed directly so that density results are available in real time. This type of system is most desirable when used with a volumetric flowmeter. Then, mass flow rate or total mass transfer can be computed, and the results made available in real time.

CONCLUDING REMARKS

This report is the last in a series of reports that describe the development of a system, based on an open-ended microwave cavity, for measuring the density of hydrogen. The system was developed to fulfill a need for an accurate way to measure the total mass transfer of liquid hydrogen as, for example, in loading space vehicles.

It was demonstrated in previous reports, that steady-state liquid-hydrogen density measurements can be made with less than 0.1 percent error. It was also shown that the presence of small, uniformly distributed gas bubbles will not appreciably deteriorate the measurement accuracy so that the technique is also useful for two-phase density measurements.

This report described a flow line section with a built-in cavity and two different instrument systems: a resonant frequency tracking system (REFTS) and a cavity tuned oscillator (CTO). These instrument systems were developed to automatically track and record the resonant frequency of the cavity so that dynamic density measurements can be made. These systems produce a signal at the cavity's resonant frequency which can be measured very accurately using a digital frequency counter. Since present commercial counters are limited to a maximum sampling rate of five samples per second, the REFTS system also provides an analog output which, although less accurate, can be used when higher response rates are needed.

At the start of this program there were no commercially available devices for measuring the density of hydrogen. Although many devices have been proposed in the intervening years based on such diverse measurements as acoustic velocity, buoyancy, momentum transfer, and nuclear magnetic resonance effects, only the capacitance sensor has been developed to commercial status. Both the capacitance sensor and open-ended cavity are based on measuring the dielectric constant of the hydrogen. The principal advantage of the capacitance sensor is that its plates or grids, which comprise the capacitor electrodes, can be formed into a great variety of shapes or cells for improved performance in making two-phase density measurements. The bubble distribution, for example, need not be uniform over the pipe cross section if the number of plates or cells is made large. However, a large number of capacitor plates in a flow line application can constitute a serious blockage to the flow. Moreover, small capacitance changes due to the capacitor plates shifting during thermal cycling can constitute a source of serious error. The principal advantages of the open-ended cavity are the absence of zero shift due to thermal cycling, minimal blockage to the flow, and inherent high precision of the measurement.

Although this entire effort was devoted to the measurement of hydrogen density, the basic technique is by no means restricted to hydrogen. It can be used for measuring the density of any material as long as there is a unique relationship between its density and dielectric constant. The system can also be used to make dynamic measurements of other material properties if these properties can be related to relative dielectric constant.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 19, 1971,
128-31.

APPENDIX - SYMBOLS

a	radius of end partition in cavity
a_o	molecular radius of hydrogen
b	radius of body of cavity
c	velocity of light
f	resonant frequency of cavity when filled with hydrogen
f_o	resonant frequency of cavity when evacuated
K	relative dielectric constant of hydrogen
K_{eff}	relative dielectric constant of mixture
K_g	relative dielectric constant of gas
K_l	relative dielectric constant of liquid
k_o	free space wave number, $2\pi f_o/c$
L	spacing between partitions in cavity
m	mass of hydrogen molecule
Q_L	loaded Q, $Q_o/(1 + \beta_1 + \beta_2)$
Q_o	unloaded Q, 2π times the ratio of energy stored in cavity to energy dissipated to cavity walls per cycle of oscillation
r_e	mean bubble radius
T	transmission factor of cavity
α	average polarizability of hydrogen
β_1, β_2	coupling coefficients for each of two loops in cavity
δ	fraction of cavity volume occupied by gas
ϵ_o	permittivity of free space
λ	wave length
ρ	mass density of hydrogen
τ	time delay
φ	phase shift
ω	angular frequency

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